SEISMIC PROTECTION OF STRUCTURES – APPLICATION OF BASE ISOLATION IN BUILDINGS

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Summary: *High seismicity at many locations in the world causes the application of massive structures which induce large inertial forces. This results in severe damage, partial or total demolition of all types of structures. Conventional aseismic design is based on the concept of increasing capacity of resistance of ductile structures using vertical elements and other stiffeners. By applying the base isolation in combination with a system for dissipation of energy, seismic protection of building is enabled without using an optional external energy, with relatively long service life of the system.*
The paper presents the basic concepts of the base isolation system, a description of the method of designing mentioned system in order to reduce the damage and ensure adequate performance of the structure. In addition it provides a wide review of the literature in the field of base isolation of buildings.

Keywords: *Inertial forces, base isolation, dissipation of energy, damage, performance*

1. INTRODUCTORY REMARKS AND TYPES OF PROTECTION SYSTEMS

Earthquakes have always been considered as one of the most severe natural disasters. They claimed many human lives and material losses, constantly forcing people to search for better protection from the devastating effects of earthquakes [5]. Although more or less present in every place across the world, it is unlikely to predict accurately the time and place where earthquakes may occur, nor their intensity through which they transmit seismic energy. Through the theory of plate tectonics modern science defines earthquakes as a result of a sudden release of energy in Earth's crust (mantle) which are then reflected as a stochastic vibrational movement of the surface layers of soil. Approximately 85% of earthquakes are of tectonic (natural) origin and they are formed by sudden shifts along the contact lines between tectonic or lithospheric plates (thickness 10-60 km) that constantly 'float' on the viscous asthenosphere. These shifts release the accumulated potential energy, which then turns to kinetic energy. Other earthquakes can occur due to volcanic or mining activities, powerful explosions, but also due to collisions

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with various celestial bodies (asteroids, comets ...). Ancient builders understood the devastating potential of earthquakes very well and reacted to them with a thoughtful way of construction, complying to the basic principles of engineering [8]:

- Choice of foundation depth, i.e. resting the structure on soil with stable properties or replacing the low-capacity soil to provide the bedding with uniformity and sufficient bearing capacity.
- Seismic isolation, i.e. application of elements for isolation and absorption of energy, as well as additional devices that mitigate the vibration process which is transmitted from ground to the building.
- Preventing solid (composite) connection between ground and the building using sand tampon, clay cushion, ring beams, metal plates, air bags and a variety of spring-based isolators.

Records of high seismicity at many locations in the world are characterized by the design spectrum. With the use of massive structures that induce large inertial forces due to earthquakes, this leads to substantial structural damage and even demolition [5]. Seismicity particularly increases in places which are seismically active but where strong earthquakes have not occurred recently. Earthquake primarily represents a process of transmission, absorption and dissipation of energy where structures are mainly demolished due to the high input energy, which can not be absorbed and dissipated through the movement of the structure and its secondary elements [12]. This fact has led to a new philosophy in seismic engineering, which consists of developing methods for identifying possibilities for modification and reduction of seismic effects on structures. As important public buildings (like hospitals, schools, police and fire stations, bridges...) should remain functional after the earthquake event, the concept of protection using base isolation (passive control of structures) has been increasingly applied [14]. Flexible structures are more susceptible to seismic actions, especially when there is no possibility of additional energy dissipation [9].

Depending on the control mode, there are three systems of protection against the earthquakes: passive, active and hybrid (semi-active). Passive systems do not use additional external energy for their work, while active systems use controllable systems which induce additional energy. Hybrid systems combine passive and active systems of protection.

The above systems include multiple methods of protection:

1. Passive protective systems are based on tuned mass damping, energy dissipation and seismic isolation.
2. Active protective systems of protection are based on active mass damping, active bracing and adaptive control.
3. Hybrid protective systems are based on active isolation, semi-active isolation and semi-active mass damping.

Passive systems are the oldest systems of protection and include seismic (base) isolation and passive (mechanical) dissipation of energy [5]. They are used both in newly designed buildings, and in existing buildings. It has been recorded that during the devastating 1995 Kobe earthquake objects with base isolation proved to be effective in reducing structural response.

Base isolation is usually installed at the base of the building or its lower part, uncoupling a structure from the ground and reducing thereby the transmission of seismic forces from

the ground. Devices used in passive protection systems are more accessible and neither require additional maintenance nor frequent servicing. Unlike them, active systems of protection imply expensive additional systems to be installed for controlling structural displacement which require careful and regular maintenance.
The above facts testify the need for protecting buildings against earthquakes using base isolation. This paper provides a summary overview of recommendations and methods for designing measures aimed at reducing seismic risk by introducing base isolation and passive control of structural behaviour in seismic regions.

2. ENSURING THE PERFORMANCE OF STRUCTURES

The approach currently used in seismic protection cannot establish the degree of damage to the structure of the object after the earthquake. Although the project level of seismic action is determined for the return period of about 500 years, it is unlikely for even a stronger earthquake to occur during the object lifetime. Deformation checks should be carried out for all the considered limit states, where the value of the permitted deformation depend on the expected level of structural behaviour during the earthquake [6]. The concept of design based on seismic performances [4] was initially given in the FEMA-273 document, and later also in similar documents.
FEMA documents [3] and [4] define four levels of structural behaviour: 1) operating, 2) immediate occupancy (IO), 3) life safety (LS) and 4) collapse prevention (CP). Each of these levels shows the expected behaviour of the object after the earthquake, describing the damage to the main and secondary structural elements, economic losses, and what interruptions can occur in the operation of the building after a seismic hazard. Seismic hazard depends on the position of the object's location relative to the active faults, as well as regional and local soil conditions. Four levels of seismic hazard were identified which correspond to different earthquake return period, while the expected behaviour of the building is given as their function, as shown in [8].
Seismic effects depend on the seismicity of the area, the adopted seismic hazard, the soil properties, the structure's dynamic properties, the available structural ductility, and the importance of the object in terms of its use. If the fundamental period of vibration of any part of the building is close to that of the soil, resonant state occurs with a large increase in seismic forces, and the structure will either demolish or adapt to the higher level of action, depending on its properties [6].
The structure's adequate performances can be ensured using the following design methods [5]:

1. Ensuring the required ductility.
2. Method of base isolation.
3. Method of controlling the dynamic response (Figure 1).

To make the structure "work" as a single body, sufficient ductility in the plastic area should be provided, which is actually the measure of post-elastic behaviour [13]. When ensuring the required ductility, the structure provides sufficient bearing capacity and ductility so that it can absorb the input seismic energy. Since the criteria for the acceptable damage level are largely economic in nature, it is irrational to design objects that behave elastically in the case of strong earthquakes. Therefore, inelastic behaviour should be ensured, but after the earthquake the structure can no longer function, nor is its rehabilitation cost-effective. That is why the method of base isolation and method of controlling dynamic response are used in designing the objects that remain in service after the earthquake.

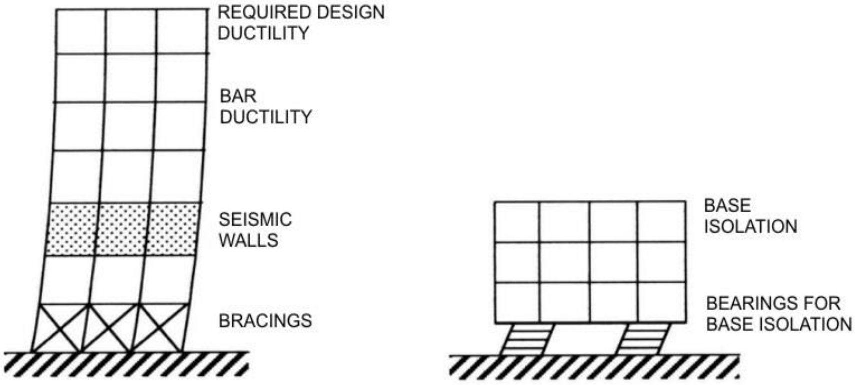

Figure 1: Schematic representation of design methods with ensuring ductility and base isolation

Using base isolation the seismic response of the structure is reduced by preventing the input of the high potential energy of the earthquake in the structure. The input seismic energy is transformed into kinetic energy, damping energy, potential energy (elastic deformation), and energy of plastic deformation (hysteresis damping). The energy is distributed differently to the above components, and it is constant when the masses and vibration frequencies are constant. The distribution of input energy in linear and non-linear structure is different [3], given the fact that in non-linear structures hysteresis energy is considerably higher than kinetic and potential energy. In contrast to hysteresis damping, viscous damping depends on vibration frequency. Damping in which periodic vibrations transform into aperiodic vibrations is named critical damping, so that the value of the structure's design damping is usually taken as 2-10% of critical damping. From the aspect of energy balance, the behaviour of ductile structures is much better than that of non-ductile structures [5].

When using base isolation the energy intake is limited by installing devices for reducing seismic energy at the level of foundation and/or by incorporating devices for energy dissipation within the structure at a certain height above foundation. All solutions are based on the lessons learned from designing foundations of machines using the base isolation method. Base isolation is mostly used in rigid structures given that they are the most threatened by high frequency and high acceleration seismic displacement [5], although it can be used for bridges and flexible structures. The aim is to extend the fundamental period of vibration of the isolated structure, making it exposed to lower seismic action, higher damping, or a combination of these effects [13]. Depending on whether the structure remains partially or completely in the elastic area, the base isolation can be partial or complete [2]. In the case of complete isolation, structural analysis can be conducted using elastic response spectrum analysis, while using partial isolation requires nonlinear time history analysis.

3. DESIGNING BASE ISOLATION IN BUILDINGS

Passive control of the structure's dynamic behaviour during seismic activities is achieved by controlling the input forces, rather than based on the capacity of structural elements. This methodology can also be used in strengthening the existing structures and for providing greater spatial comfort in buildings [5]. The design strategy is based on the starting point and feasibility of preventing coupled action of the structure and soil and preventing structural damage from seismic acceleration. This is achieved by reducing the stiffness of the structure by introducing flexible elements (isolators and dissipators) close to the building's base. Additional damping is ensured to the level of limiting the displacement of the isolators to an acceptable value.
Passive protective systems do not require additional external energy. In addition to using base isolation to increase the fundamental period of vibration and filter the displacement before it is passed into the structure, passive systems use passive control devices (dissipators usually made of mild steel) which dissipates the input energy, while damping is adjusted for optimum structural behaviour [11]. When used in combination with bearings, dissipation devices usually have an appropriate gap enabling them to be activated only in the event of exceeding seismic displacement [12]. Base isolation systems operate in serial connection with the structure, while the passive control system (dissipation) operates in parallel.
Base isolation uses bearings made of natural rubber, bearings with large damping, elastomeric bearings with laminated rubber, laminated lead-core bearings, sliding teflon bearings, or friction pendulum bearings, and combination of springs and viscous dampers [5].

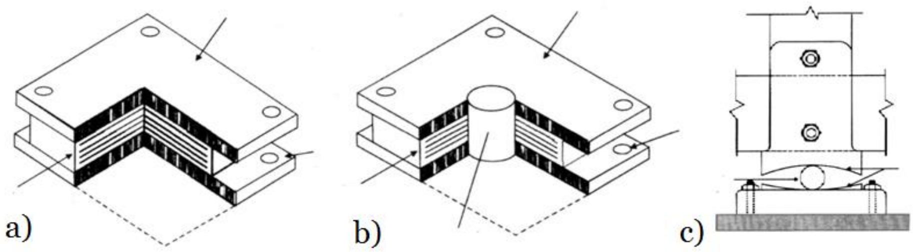

Figure 2: a)Elastomeric bearing, b)lead core bearing, and c) friction pendulum

Modern isolation systems include elastomers and sliding supports, with or without a damper or damping mechanism [12]. Elastomeric bearings (Figure 2.a) can be produced from rubber with high damping capacity, or can be provided with lead core (Figure 2.b), or energy can be dissipated by friction using slide bearing, and there is also a possibility for self-centering. Curved sliding surfaces can also be used (Figure 2.c). Passive energy dissipators are used to dissipate energy during earthquakes and reduce their impact in the structure. They can be classified as hysteresis and viscoelastic dissipators [5].
Hysteresis dissipators are based on the plastification of metals when bending, shearing and torsion (metal dampers), and when sliding in the case of friction dampers. All these devices are activated in the event of system movement.

Viscoelastic systems include viscoelastic bodies and fluids and they are dependent on the speed of displacement, and some of the frequencies.
Isolated structures are designed in a way to resist small or medium earthquakes without damage to structural elements and non-supporting components, while remaining without damage to the isolation system and a major damage to structural elements and non-supporting components in the case of strong displacement of the soil.
Base isolation should ensure the system to remain stable for the required design displacement, provide increased resistance to increased displacement, not to damage under repeated cyclic loading, and have adequate damping properties and proper force-displacement ratio. Isolation systems have four basic types of force-displacement ratios. They are shown idealized in Figure 3, for the same displacement D for design earthquake [10].

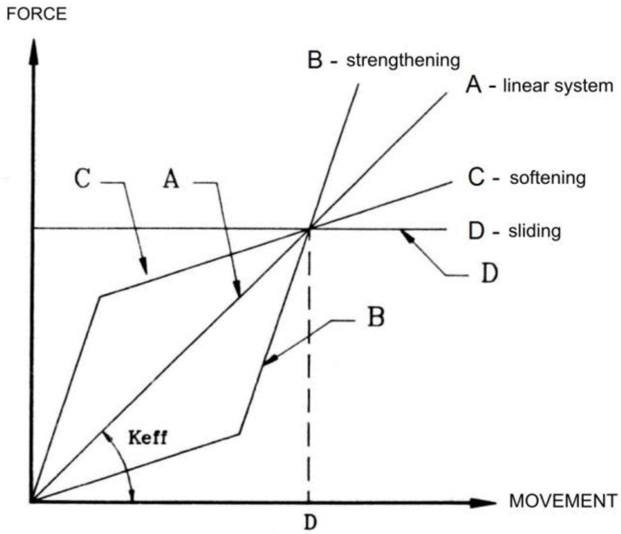

Figure 3. Idealized force-displacement diagram of the isolated system

The isolation system is usually installed between the foundation and the structure, preventing the displacement from being transmistted from the soil to the structure, i.e. it prevents the coupled vibration of soil and the structure. Isolation bearings (particularly elastomer bearings) are usually designed to have high vertical and low horizontal stiffness [13]. Due to the pronnounced possibility of deformation in horizontal direction, they can provide sufficient stiffness for carrying operational loads only for wind and weaker earthquakes. One of the ways to reduce their lateral deformability is to model their cores with lead pins (popular in the United States and New Zealand), shown in Figure 2.a. It is known that consideration of earthquakes is reduced to analyzing forced vibrations caused by the movement of base-soil on which the structure is founded [7]. When considering the dynamic properties of base isolation, a single storey structure can be modelled with a linear isolator (Figure 4). It is assumed that the mass and stiffness of isolated upper structure are much larger than the mass and stiffness in devices for seismic isolation.

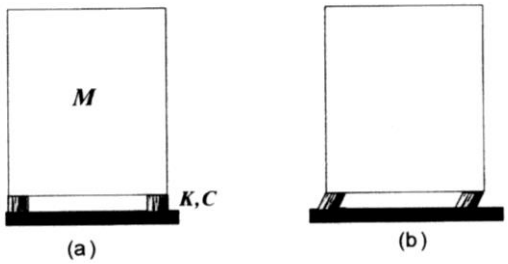

Figure 4: Isolated structure: a) initial shape, and b) deformed shape

Taking the isolated part of the building as a stiff mass, the base isolated building can be simulated with a system of single degree of freedom (SDOF), for which the equation of motion can be written as:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = -M\ddot{u}_g(t) \tag{1}$$

where M, C and K are the system's mass, damping and stiffness, respectively; $u(t)$, $\dot{u}(t)$ and $\ddot{u}(t)$ are the displacement, velocity and acceleration of the mass, respectively; $\ddot{u}_g(t)$ is the function of soil acceleration.

Using Duhamel's integral, the response $u(t)$ of the base isolated system can be expressed as:

$$u(t) = \frac{-1}{\omega_d} \int_0^t \ddot{u}_g(\tau) \exp[-\xi\omega(t-\tau)] \sin \omega_d (t-\tau)\, d\tau \tag{2}$$

where ω is the fundamental frequency, ω_d is the damped fundamental frequency, while ξ is the damping coefficient, which are given as:

$$\omega = \sqrt{\frac{K}{M}}, \omega_d = \omega\sqrt{1-\xi^2}\ , \ \xi = \frac{C}{2M\omega} \tag{3}$$

while the corresponding frequencies of vibration are:

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{M}{K}},\ T_d = \frac{2\pi}{\omega_d} = \frac{T}{\sqrt{1-\xi^2}} \tag{4}$$

For the given soil acceleration $\ddot{u}_g(t)$ acceleration of the SDOF system depends only on T and ξ of the structure. Thus, the greatest deformation for a specific earthquake can be calculated using equation (2). By repeating this process for a wider range of the period T, while keeping damping at constant level a curve is obtained, while by varying the damping ξ deformation response spectra can be obtained for the SDOF system under the given earthquake [1]. The pseudo-acceleration response $A(t)$ of the system is calculated using the $u(t)$ value as follows:

$$A(t) = \omega^2 u(t) = \left(\frac{2\pi}{T}\right)^2 u(t) \tag{5}$$

Multiplying the value of $A(t)$ with the mass M gives the equivalent static force (shear force) in the base of the given structure.

The philosophy behind the base isolated structure is aimed at extending the fundamental period of vibration, which reduces the earthquake induced shear force at the base, providing additional damping *f* or reducing the relative displacement along the isolator itself [5]. More benefit from base isolation system is achieved in rigid structures where the fundamental period of vibration of the fixed structure is less than 1.0 second. In these structures, the fundamental period can be extended to 1.5 to 2.5 seconds by installing base isolation system [14]. This technique is applicable in low and medium-high buildings, and is less effective in very tall buildings, given that the fundamental periods of vibration increase with the height of the building.

In solid ground, soil acceleration consists mainly of high frequency components, with low frequencies prevailing in soft ground. Therefore, base isolation is avoided in founding on soft ground because it is more harmful than helpful. In this case, the viscous and hydraulic dampers are used [1] and [14].

4. RECOMMENDATIONS FOR BASE-ISOLATED STRUCTURES

When designing base isolation the following should be ensured [14]:

1. Sufficient horizontal flexibility in order to maximize the fundamental period and the required spectrum, except at locations with soft ground.
2. Sufficient capacity of energy dissipation to restrict the displacement along the isolator.
3. Adequate stiffness which will not lead to difference in behaviour under operational load of base isolated structures and those fixed in the base.

Combinations of elastomeric bearings and dampers are widely used as seismic isolators (Figure 2). With a special rubber they achieve effective damping of 10-20% of critical damping [5]. Friction pendulum systems are also often used given their low price and reliability of material (teflon and stainless steel) which forms the slide bearings, as well as to avoid torsion effects.

According to [10], the isolator should play a dual role: in addition to carrying the maximum gravity load, it should contribute to the relocation of the fundamental period and dissipation of energy of the isolated structure during the earthquake. This requires the following steps to be implemented:

a. Identifying the smallest surface area in the base and installing the isolator below the maximum gravity load.
b. Calculating the smallest isolator dimensions which should lead to the desired value of relocation of the fundamental period and reduction of seismic forces.
c. Identifying the isolators's damping coefficient which controls the displacement of the structure within the calculated values under the influence of wind.
d. Checking the performance of isolators under gravity load and temperature, wind and seismic effects.

5. CONCLUDING REMARKS AND CONCLUSIONS

In earthquake engineering there is a constant effort to improve the methods of protection of buildings from the harmful effects of earthquakes. Damage to non-supporting and other non-structural elements, equipment, installations and the like are lower in stiffer

systems with the required ductility achieved. It is still not enough for achieving adequate protection, so that solutions are focused on passive and active seismic protection [5].
In the field of protection against seismic hazard, the highest quality guidelines in designing base isolated buildings can be found in the US FEMA regulations, along with the published recommendations and comments on the application of isolation devices and energy dissipators in existing and new buildings [3] and [4]. It is recommended to use linear and non-linear analyses which are consistent with the usual methodology of conventional design and allows the application of non-linear static analysis [7]. Technical regulations in the field of seismic isolation are frequently changed. One example for this are the revised FEMA recommendations from 1991, which were supplemented in 1995-97 with sliding systems and improved methods of analysis.
Seismic isolation can ensure substantial reduction in seismic forces so that the structure remains in the elastic range of response. This is achieved by various forms of passive and active control systems, which enable preventive protection of structures against seismic actions [13]. The attention should be particularly focused on conflicting demands as the use of isolators has regularly been associated with the emergence of large-scale displacement during strong earthquake actions, while the conditions of usability require limited structural displacement. Extending the fundamental period of structural vibration helps in keeping the distance from the prevailing frequency of soil oscillation, which is 0.2-1.0 seconds for most earthquakes, in order to avoid the phenomenon of resonance.
The application of passive protection systems carries lessons and surprises [1]. To avoid any misconception and optimize the response of the isolator, soil displacement should be carefully modelled, damping estimated and performance criteria defined. It is believed that the future of passive control lies in the application of intelligent materials, [9] and [10].

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СЕИЗМИЧКА ЗАШТИТА КОНСТРУКЦИЈА - ПРИМЕНА БАЗНЕ ИЗОЛАЦИЈЕ КОД ЗГРАДА

Резиме: *Висока сеизмичност на многим локацијама у свету условљава примену масивних конструкција које индукују значајне инерцијалне силе настале дејством земљотреса. Резултат тога су велика оштећења, делимична или тотална рушења свих типова конструкција. Конвенционално асеизмичко пројектовање заснива се на концепту повећања капацитета отпорности конструкција применом дуктилних вертикалних елемената и других укрућења. Применом базне изолације у комбинацији са системом за дисипацију енергије, сеизмичка заштита објекта је омогућена без коришћења додатне спољне енергије, уз релативно дуги експлоатациони век система.*
У раду су приказане основне теоријске поставке система базне изолације, опис метода пројектовања поменутог система у циљу смањења оштећења и обезбеђења адекватних перформанси конструкције. Такође је дат и широк преглед литературе из области базне изолације код зграда.

Кључне речи: *Инерцијалне силе, базна изолација, дисипација енергије, оштећење, перформансе*